Model experiment for ransport of Heat, Water and Vapor within Soil-Plant-Atmosphere System and its Numerical Simulation Model

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Abstract

Earth surface has been changed with advanced of urbanization and deforestation in recent years. As the result of these artificial or natural alterations of the surface, it comes to be suggested in many fields that microclimate near the surface has been changed because of the variation of momentum, latent and sensible heat fluxes. Then, it is very important to predict the change of microclimate near the surface not only for the analysis of local climate like the heat island phenomena and air pollution in urban area but also for the climate change prediction of global scale. In these backgrounds, it is necessary to understand in detail and construct the prediction model for the transport of heat, water vapor and momentum in the air and soil near the surface.

In this paper, we conducted two model experiments and compared these results with those of simulation model (Multi-layer soil-plant-atmosphere model). One is evaporation experiment from bare soil using a column container with a depth of 650mm and a diameter of 200mm. The other is for experimentally planted azalea in the same size column. It is shown from these evaluations that the numerical model we employed can reasonably well predict the behaviour of variables within soil-plant-atmosphere system.
Keywords: Model experiment, Soil-Plant-Atmosphere system, Microclimate analysis, Numerical model

1 Introduction

After the 1960s, air pollution posed a serious problem all over the world, and this developed the study on the atmosphere which was called atmospheric boundary layer. From a series of this study, theoretical system of the stmospheric boundary layer above the horizontal ground surface can be referred to be completed mostly. But actual ground surface includes mountains, valleys, forests, and cities, so the structure of it is very complicated. Therefore, the simulation model which can represent the phenomenon occurred at the complicated ground surface is needed.

When examining the various soil-plant-atmosphere models proposed in the literature, it can be seen that one or several compartments of the model are generally very detailed, whereas the other compartments are not detailed well. So we tried to build a model, including the main physical model, and calculating the each compartments divided into many layers. In this paper, one-dimensional Multi-layer soil-plant-atmosphere model which is based on the model of Kondo et al. [1], [2] was developed to reproduce the relationship of the momentum, heat, and water vapor between the vegetation, atmosphere and soil.

2 Numerical model

This model consists of atmosphere part, vegetation part and soil part. Schematic diagram of this model is shown in Fig.1.The atmosphere part consists of prognostic equations for horizontal wind components, potential temperature, and

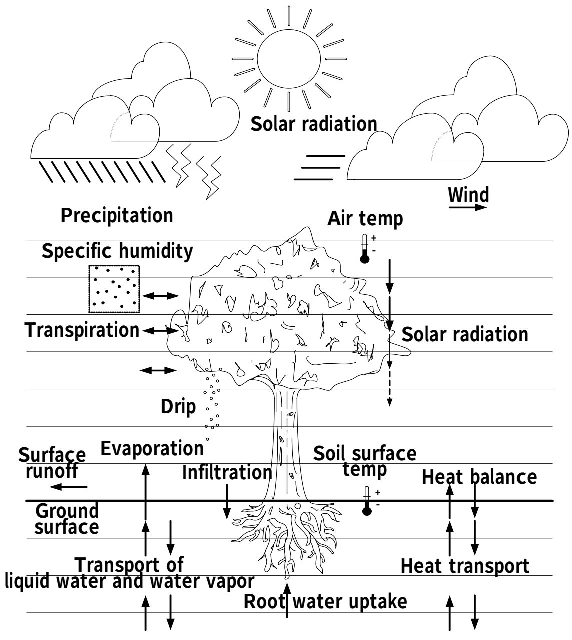


Fig.1 Schematic diagram of Multi-layer Soil-Plant-Atmosphere Simulation model

	Experiment1	Experiment2	Experiment3
Period	6-20 Aug. 2002	15-21 Sep. 2003	19-25 Aug. 2003
Initial time	15:00	0:00	0:00

Rainfall	2^{nd},5^{th},12^{th}	5^{th}	—
Azalea	—	55cm	55cm
Fallen leaves	—	—	1cm

specific humidity. The turbulence coefficient is determined by *k-ε* model proposed by Liu et al. [3]. The vegetation part consists of a heat and water budget equation for the leaf surface temperature and prognostic equation for the vertical water flux in the canopy. The soil part consists of transport equation for heat, liquid water, and water vapor in soil air. In this paper, variation of liquid water in soil caused by root water uptake is considered. Also, the fallen leaves on the soil surface are regarded as a part of vegetation leaves that have no transpiration.

3 Model experiments for evapotranspiration of heat & water

Evapotranspiration experiments for model validation were conducted from 2002 to 2003. In particular, three periods which have the feature in ground surface were selected. Summary of three experiment's period are shown in Table.1. The site was situated at the campus of Osaka University, Osaka, Japan (35 ° N, 135 ° E). Experiments were conducted using a column container with a depth of 600mm and a diameter of 200mm. The column is made from vinyl chloride and was filled up with the sample soil. Experiment1 remained to be bare soil, and Experiment2 and 3 were experimentally planted azalea. Thermocouples (copper-constantan JIS:T, Φ=0.35mm) and microtensiometer (SANKEI, SK-5608) were installed to observe the soil temperature and volumetric water content in soil at eight points (3cm, 4.5cm, 10cm, 16cm, 26cm, 46cm, 65cm)

Table.2 Physical characteristics of the sample soil and Azalea

	Unit	Value
Soil characteristic		
Sand	%	16.0
Silt	%	33.8
Clay	%	50.2
Density	kgm^{-3}	1018.0
Field capacity	m^3m^{-3}	0.50
Saturated volumetric water content	m^3m^{-3}	0.63
Saturated hydraulic conductivity	ms^{-1}	7.54×10^{-6}
Vegetation characteristic		
Height	m	0.55
Maximum leaf area density	m^2m^{-3}	2.07
Minimum stomatal resistance coefficient	sm^{-1}	320
Resistance coefficient	—	0.2
Leaf gradient	—	0.5
Leaf emission rate	—	1.0
Leaf area density at fallen leaves	m^2m^{-3}	9.4

respectively. Moreover, weighing machine (AND,GP-60K) was set at the bottom of a column container to observe the evapotranspiration speed by carrying out continuation measurement of the weight change accompanying evapotranspiration. Transpiration was measured by dynagage (DYNAMAX, SGA 10-WS). Meteorological data in vegetation and atmosphere were also measured. Measurements include air temperature, air humidity, wind speed, rainfall and solar radiation. Leaf temperature was measured using the thermocouples, too. These automatic measurements were performed under different conditions. Each measurement interval was performed in 10 minutes. The characteristic of the soil and vegetation used in this study is shown in Table.2.

4 Comparison of calculated and observed results

4.1 Comparison of calculated and observed results for Experiment 1

Fig.2 shows the microclimate data. In this period for two weeks, the 2^{nd}, 5^{th}, and 12^{th} day from the observation start had a rainfall described in Fig.2(c). Because of the daily variation of solar radiation, air temperature had a daily variation as if it was in proportion to that of solar radiation. But in rainy time, it could be seen that air temperature fell down rapidly. Comparatively weak wind velocity $4ms^{-1}$ or less was confirmed from Fig.2(b). Fig.3 presents the soil temperature. From the variation of this result and air temperature, it turned out that soil temperature near the surface had a form which followed air temperature. And it could be seen that the range of amplitude of diurnal variation of soil temperature decreased exponentially with depth and became insignificant at a depth of the order of 46cm or less. Calculated values of soil temperature had the same variation and could reasonably well predict the observed data. Fig.4 shows the volumetric water content in soil. When it continued to be no rainfall, variation that the measured and calculated volumetric water contents were gradually decreased from the soil surface toward the lowermost soil layer was confirmed. And from the diurnal change, it turned out that soil was dried well during daylight, but was not dried well during nighttime. This variation affected the evaporation rate shown in Fig.5. Evaporation rate from the soil surface was increased during daytime, while the value of it was nearly zero during nighttime. When it rained, on the other hand, volumetric water content increased rapidly. This model represented this phenomenon, but water permeation speed from soil surface to deep soil calculated faster than the observed results. This is because it is said that soil characteristic, such as hydraulic conductivity and matric potential, present a different properties between the drying process and wetting process, but in this model, these soil properties are not considered.

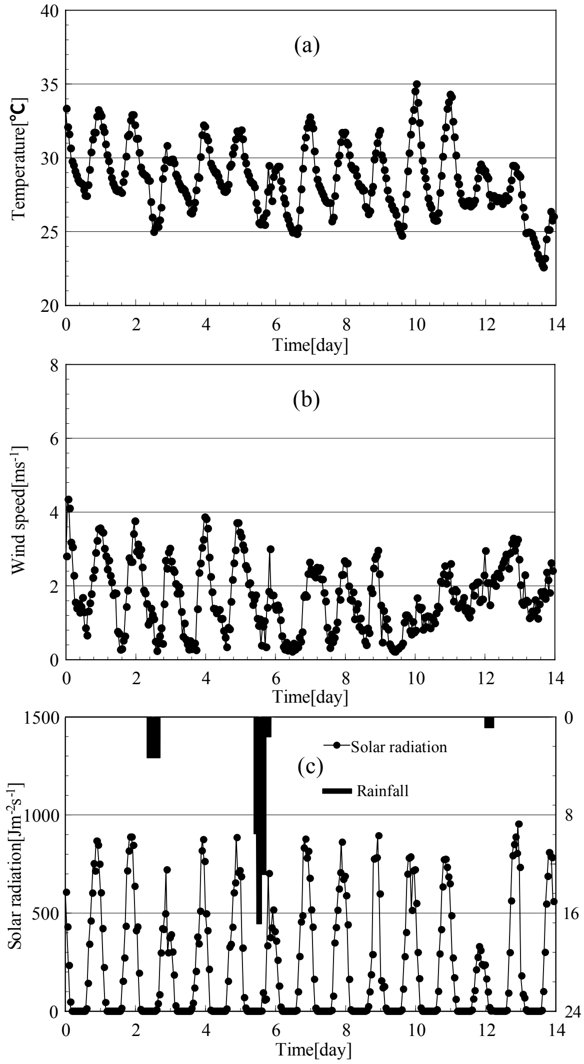


Fig.2 Meteorological conditions during the period of Experiment 1
(a) air temperature (b) wind speed (c) solar radiation and rainfall

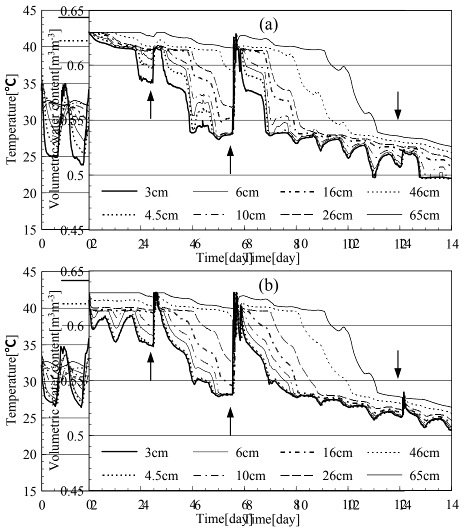


Fig.3 Comparison of soil temperature
(a) observed (b) calculated
↑ initial time of rainfall

Fig.4 Comparison of volumetric water content (a) observed (b) calculated
↑ initial time of rainfall

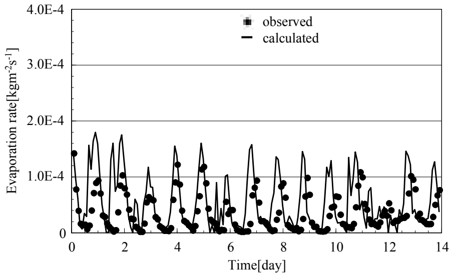


Fig.5 Comparison of evaporation rate for Experiment 1.
● observed — calculated

4.2 Comparison of calculated and observed results for Experiment 2

Fig.6 shows the difference of microclimate. Solar radiation was gradually extinct from the top of the vegetation. And the extinction ratio became maximum at 25-40cm, where the leaves of azalea are crowded. As a result, solar radiation reached soil surface was about 10-15% of their total composition. Also, it can be seen that calculated solar radiation inside the vegetation was underestimated compared to the observed data. Variation of wind speed was similar to the solar radiation, and the extinction ratio became a maximum at 25-40cm height. From the observed data, wind velocity became large at the stem of azalea again, but in this model, since the gradient diffusion model was used, calculation results of wind velocity could not represent this variation. Vertical profile of temperature is shown in Fig.6(c). It was confirmed that this model underestimated the temperature inside the vegetation during the daytime. One contributed factor of this error may be the difference of solar radiation inside the vegetation.

Underestimating solar radiation caused the underestimate of the sensible heat flux from vegetation, so air temperature estimated low. Moreover, the installed cover so that solar radiation might not heat the thermocouples directly might not ventilate enough, so the observed conditions and calculated conditions are not strictly agreed. Fig.7 shows the calculated and observed soil temperature and Fig.8 shows the volumetric water content. Evaporation rate and Transpiration rate are shown in Fig.9. Calculated soil temperature was underestimated because of the undervaluation of solar radiation got to the ground surface. This result had an effect on the evaporation rate, and calculation result of evaporation rate was underestimated, too. As for the volumetric water content,

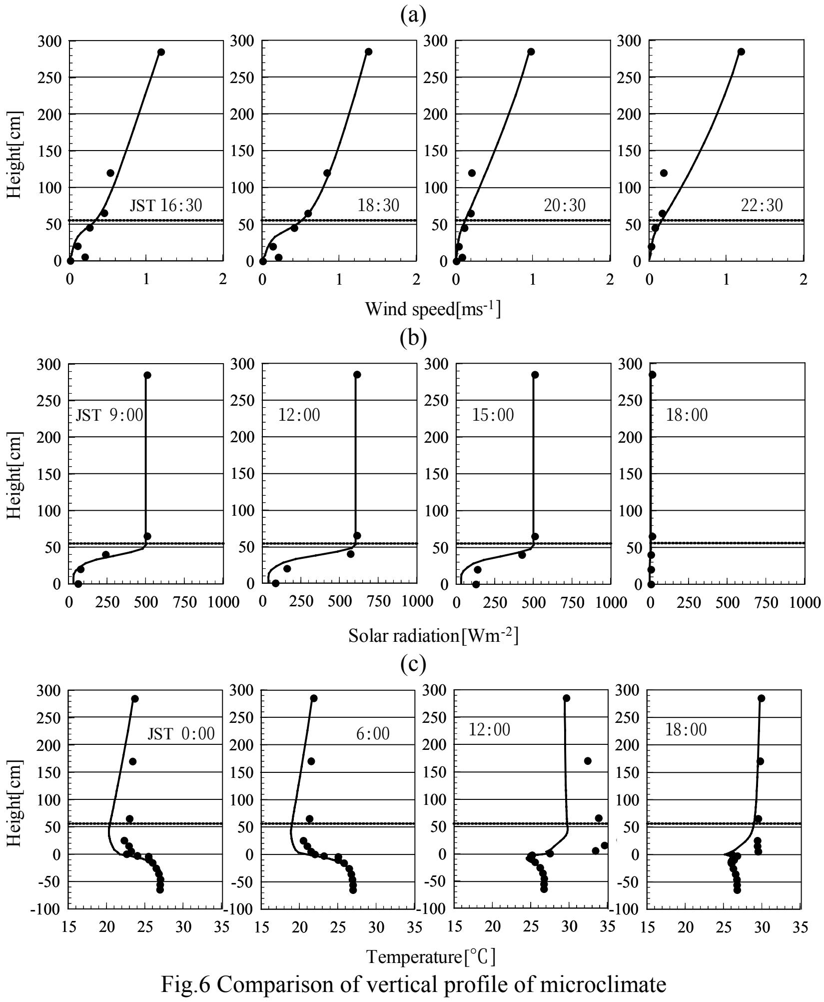
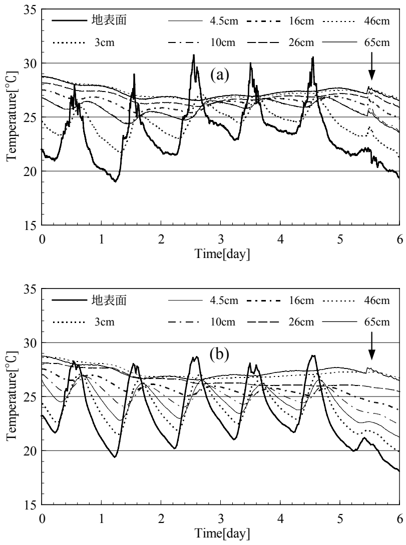


Fig.6 Comparison of vertical profile of microclimate

● observed — calculated ･･･ top of the vegetation (55cm)

(a) wind speed (b) solar radiation (c) temperature

JST : Japan Standard Time



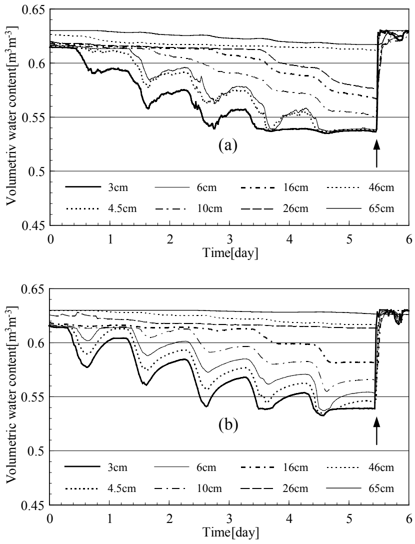


Fig.7 Comparison of soil temperature
(a) observed (b) calculated
↑ initial time of rainfall

Fig.8 Comparison of volumetric water content (a) observed (b) calculated
↑ initial time of rainfall

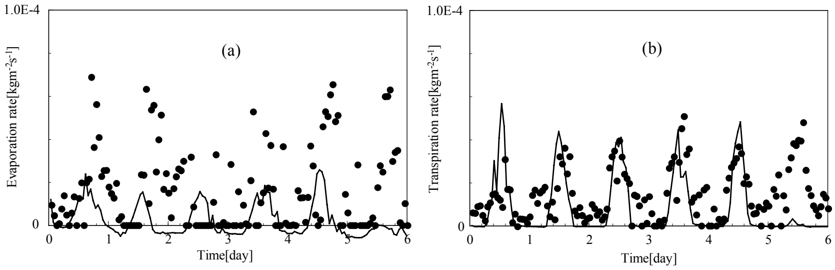
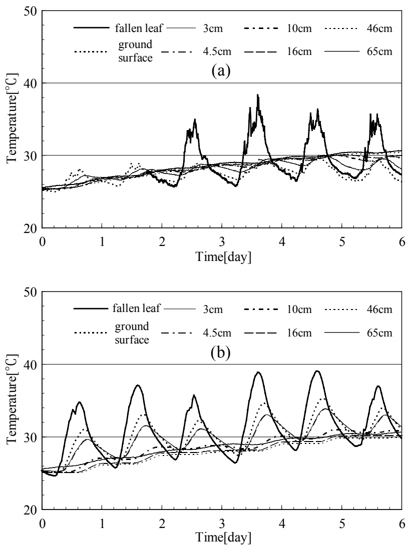


Fig.9 Comparison of evaporation rate for Experiment 2.
(a) evaporation rate (b) transpiration rate
● observed — calculated

soil near the surface gradually dried with a concavo-convex variation. It is thought that soil near the surface had root, it dried remarkably by evaporation and transpiration in daytime. In nighttime, on the other hand, water transportation from deep soil was promoted. This variation was represented by calculation results, it can be said that this model which took the root water uptake process into consideration has reproduced this phenomenon well.

4.3 Comparison of calculated and observed results for Experiment 3

Fig.10 and Fig.11 show the time variation of soil temperature and volumetric water content, respectively. Fig.12 is the result of evapotranspiration. Microclimate showed the same feature as the Experiment 2. From the result of Fig.10, temperature on the fallen leaves surface reproduced comparatively well, temperature near the soil surface was overestimated and a maximum of 3℃ error was checked. This is because large amount of heat was transported to the soil surface due to overestimation of heat transfer coefficient for litter layer, that was caused by the assumption that there is no evaporation in the litter layer. As for the evapotranspiration, the amount of evaporation had a large error immediately after a survey start. One reason for this error is the overestimate of soil temperature, the other is that the reduce effect of evaporation of the fallen leaves themselves is not taken into considered. Due to this evaporation error, volumetric water content had a large error during the first three days.



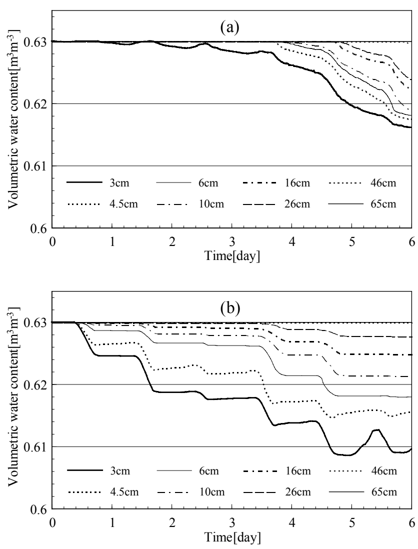


Fig.10 Comparison of soil temperature (a) observed (b) calculated

Fig.11 Comparison of volumetric water content (a) observed (b) calculated

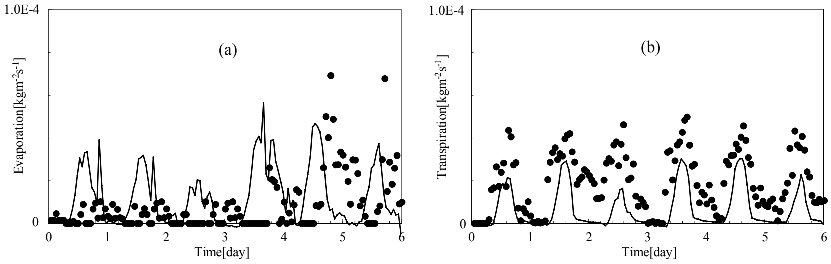


Fig.12 Comparison of evaporation rate for Experiment 3.
(a) evaporation rate (b) transpiration rate
● observed ― calculated

5 Conclusion

In this paper, one-dimensional multi-layer soil-plant-atmosphere simulation model was developed to predict the microclimate near the soil surface. At the same time, to verify the accuracy of the model, model experiment on evapotranspiration was carried out. By comparing the calculation results with observed data, microclimate within the vegetation and heat and water transportation were represented well, so good application of the model was assured. But it was confirmed underestimation of solar radiation within the vegetation (limit of 2-stream model) and a lack of reduce effect of evaporation of the fallen leaves.

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